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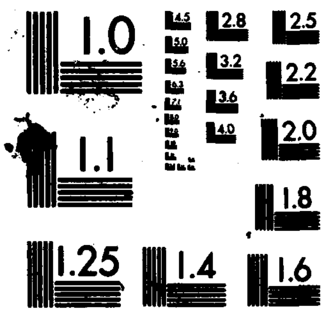

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PHASE CONJUGATE OPTICS AND ITS POTENTIAL APPLICATIONS

by

Wu Cunkai and Fan Junyin

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PHASE CONJUGATE OPTICS AND ITS POTENTIAL APPLICATIONS

Wu Cunkai and Fan Junyin

Abstract: In this paper the principles, prospects and potential applications of phase conjugate optics, in particular degenerate four-wave mixing, are reviewed.

1. Introduction

It has long been clearly understood that a phase-distorted wave-plane may be completely compensated by its own phase conjugate wave-plane. This situation may be simply illustrated by Fig. 1. If a theoretical plane wave is propagated through a phase-distorting medium, its wave-plane will be distorted as shown in Fig. 1(a). If this distorted wave-plane is then reflected by a conventional mirror back through the phase-distorting medium, the result will be a wave-plane with twice the distortion, as shown in Fig. 1(b). Then if the conventional reflecting mirror is replaced by a nonlinear reflecting mirror, as a result of the nonlinear effect, the reflected wave-plane will become the phase conjugate of the incident wave-plane, and so, when this reflected wave-plane is reflected back through the phase-distorting medium once again, it will undergo complete correction, as shown in Fig. 1(c).

Clearly, such phase conjugate techniques are of great practical significance in the fields of information processing, instantaneous storage and retrieval of information and in particular in technologies concerned with

correcting atmospheric distortion or phase distortion caused by optical chaining. What is the most convenient way to obtain a phase conjugate wave-plane?

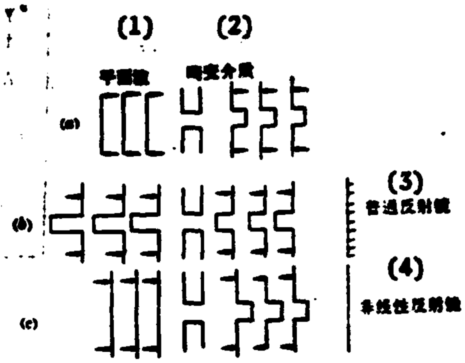

Fig. 1. Wave-plane distortion and nonlinear phase conjugate compensation process.

Key: (1) Plane wave; (2) Distorting medium; (3) Conventional reflecting mirror; (4) Nonlinear reflecting mirror.

2. Phase Conjugate Wave Generation Methods

As early as 1972, B. Ya. Zel'bovich et al. [1] discovered the phase conjugate relationship between the wave-planes of stimulated Brillouin scattered backward waves and excited waves. Later they also discovered that stimulated Raman scattered backward waves and excited waves were in a phase conjugate relationship [2]. However, because of the Stokes' back-scattering generated in the stimulated Raman scattering and because the incident excited wave exhibited an oscillator quantum energy frequency shift, the conjugate relationship was missing one phase factor.

$$\exp[-i(1-k_L/k_s)q^2/2k_LZ],$$

where K_L and K_S are the wave vectors of the excited wave and the scattered wave respectively; $q = \theta k_L$ and θ are the angular spectra of the excited wave. However, since $k_L/k_2 << 1$ (generally speaking, the Raman scattering oscillator energy $<3x10^3$ cm), then $\exp[-i(1-k_L/k_s)q^2/2k_LZ] \approx 1$. In fact, strictly speaking, in stimulated scattering, only the forward-scattered wave and the

back-scattered wave have a phase conjugate relationship [3]. Because the Brillouin phonon energy is very low (<10 cm), in cases of stimulated Brillouin scattering, it may be considered that the back-scattered wave and the excited wave have a phase conjugate relationship. In fact it is because of this characteristic of phase conjugation that the directivity of the stimulated back-scattered wave clearly changes with a consequent large increase in the brilliance. In 1976 while working on the optic fiber transmission of three dimensional images, A. Yariv [4] proposed the use of three-wave mixing to obtain the phase conjugate of the original wave. In 1977 R. W. Hellwarth [5] proposed the use of degenerate four-wave mixing to obtain the phase conjugate of the incident wave, and, by using a CS_2 transparent liquid medium, demonstrated experimentally this characteristic of phase conjugation. In 1977 C. V. Heer and P. F. McManamon [6] demonstrated the phase conjugate characteristic of the optical echo.

However, at present, the most promising and the most accepted method of obtaining the phase conjugate of an incident wave is the technique using four-wave mixing. This paper will briefly elaborate on the prospects, operating principles and potential applications of four-wave mixing phase conjugate optical research.

3. The Operating Principles of Degenerate Four-Wave Mixing

After Hellwarth et al. [5-7] made the first observations of the degenerate four-wave mixing effect in a Kerr nonlinear liquid medium CS_2, many laboratories have carried out research into the degenerate four-wave mixing effect in transparent media and in resonant or near-resonant absorbers [8-16].

Yariv [17-18] and Hellwarth [19] carried out detailed analysis of the operating characteristics of degenerate four-wave mixing. We will now explain only the basic theory. Fig. 2 shows the geometry of each beam in a four-wave mixing process.

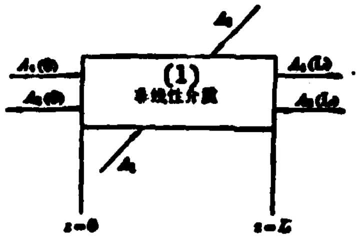

Fig. 2. Basic geometry of degenerate four-wave mixing.

Key: (1) Nonlinear medium.

With plane waves, the electric field of each wave may be shown by the formula:

$$E_i(\boldsymbol{r}, t) = \frac{1}{2} A_i(\boldsymbol{r}) \exp[i(\omega_i t - \boldsymbol{k}_i \cdot \boldsymbol{r})] + C.C.$$

where $A_i(r)$ is the resonance amplitude. In Fig. 2, A_1 and A_2 are non-depleted pump waves: A_1 is a retroflected wave; A_4 is an incident wave; the length of the nonlinear medium is L.

According to nonlinear polarization theory, the strength of the induced polarization in a nonlinear medium is

$$\begin{aligned} &P^{NL}(\omega_4 = \omega_1 + \omega_2 - \omega_3) \\ &\quad = \frac{1}{2} \chi^{(3)} A_1 A_2 A_3^* \exp[i(\omega_1 + \omega_2 - \omega_3)t \\ &\quad - (\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}_3) \cdot \boldsymbol{r}], \\ &P^{NL}(\omega_3 = \omega_1 + \omega_2 - \omega_4) \\ &\quad = \frac{1}{2} \chi^{(3)} A_1 A_2 A_4^* \exp[i(\omega_1 + \omega_2 - \omega_4)t \\ &\quad - (\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}_4) \cdot \boldsymbol{r}]. \end{aligned}$$

As can be seen from this formula for the strength of the induced polarization, if $\omega_1 = \omega_2 = \omega$, and if the two waves are propagated in opposite directions, then $k_1 + k_2 = 0$, and then, if $\omega_4 = \omega$, then $\omega_3 = \omega$, and $k_3 = -k_4$. This demonstrates that the frequency of all four waves in four-wave mixing is ω, and the direction of propagation of the waves generated is opposite to that of the incident object wave. This type of four-wave mixing is therefore degenerate four-wave mixing.

Now if

$$P^{NL}(\omega_3=\omega)=\frac{1}{2}\chi^{(3)}A_1A_2A_4^*\exp[i\omega t+k_3\cdot r],$$

then $A_3\propto A_4^*$. The significance of this is that in degenerate four-wave mixing, the retroflected wave A_3 and the incident object wave A_4 are in a phase conjugate relationship. This process may be set up as a real-time holographic process as shown in Fig. 3. In the process of holographic recording, the signal beam A_4 and the reference beam A_1 are projected at a certain angle upon the holographic plate.

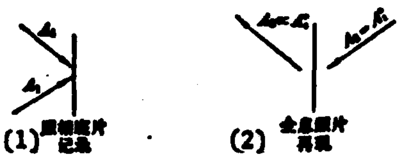

Fig. 3. Real-time holography.

Key: (1) Recording on the holographic plate; (2) Reproducing the hologram.

The holographic plate transparency function is

$$T\propto(A_4+A_1)(A_4+A_1)^*$$
$$=|A_4|^2+|A_1|^2+A_4A_1^*+A_1A_4^*$$

If the reproducing illumination beam is $A_2+A_1^*$, then propagated in the opposite direction to beam A_1 will be the diffraction field

$$A_3=TA_2\sim(|A_4|^2+|A_1|^2+A_4A_1^*+A_1A_4^*)A_1^*$$
$$=(|A_4|^2+|A_1|^2)A_1^*+(A_1^*)^2A_4+|A_1|^2A_4^*$$

We are not interested in the fact that the first term of this formula is proportional to the incident field $A_1^*=A_2$; the second term $(A_1^*)^2A_4$, has a phase factor $\exp[-i(2k_1-k_4)\cdot r]$, in the thick holographic plate, and therefore as this is a non-phase-matched term, it has no radiation; the term in which we are interested is

$$A_3\sim|A_1|^2A_4^*=A_1A_1^*A_4^*=A_1A_2A_4^*$$

This is in fact the conjugate of the original object wave A_4. This reproduction wave is very similar to the preceding discussion concerning nonlinear polarization strength.

To find the resonance amplitude A_3 of the backward conjugate wave, we may use standard nonlinear optic methods. We may substitute the nonlinear induced polarization strength P^{NL} in the equation of wave motion

$$\nabla \times \nabla \times E + \frac{\varepsilon}{C^2} \frac{\partial^2 E}{\partial t^2} = -\frac{4\pi}{C^2} \frac{\partial^2}{\partial t^2} P^{NL}$$

In non-pump-depletion and heat insulated approximations

$$\left| \frac{\partial^2 A_i}{\partial z^2} \right| \ll \left| ik_i \frac{\partial A_i}{\partial z} \right|$$

we may derive the equation for the A_3 and A_4^* coupled wave:

$$\frac{dA_3}{dz} = i\kappa^* A_4^*$$
$$\frac{dA_4^*}{dz} = i\kappa A_3$$

Assuming the wave A_4 is propagated in direction Z, the coefficient of coupling in the formula is

$$\kappa = \frac{2\pi\omega}{Cn} \cdot \chi^{(3)} I,$$

in which I is the strength of the pump wave; n is the refraction index of the medium. Under certain boundary conditions, if we try to obtain the equation for the coupled wave, we can obtain strict values for A_3 and A_4^*, and thus we can obtain the nonlinear index of refraction as

$$R = \frac{|A_3(0)|^2}{|A_4(0)|^2} = \tan^2(|\kappa| L)$$

and the nonlinear reflection index and $|\chi^{(3)}|^2$ of the nonlinear medium and the square of the effective length of the medium will be proportional. For further details refer to bibliography [17] and [19].

In more resonant absorbers we must take into consideration the interaction of the radiation field and the atomic system. Now because pump

saturation effect, transverse relaxation time and longitudinal relaxation time of the energy level, the pump beam and detuning in the center of the spectral lines of the absorber all have an effect, handling absorbent media is somewhat more complicated. The reader may refer to bibliography [20] and [21]. In bibliography [21], we derived even stricter results.

In the above discussion of theoretical processes, whether degenerate four-wave mixing or three-wave mixing (stimulated Brillouin scattering and stimulated Raman scattering), we have considered the pump wave to be stable and have assumed it to be a constant. This is appropriate in small-signal approximations. However, in reality, the signal beam undergoes conversion in nonlinear coupling with the pump beam. Thus, generally speaking, the pump wave should not be considered a constant, particularly when generating a backward wave oscillation. In such conditions, we should consider large-signal theory. Recently H. Hsu [22] has derived a large-signal theory for degenerate four-wave mixing. In small-signal approximations, three-wave mixing and four-wave mixing have no major differences. But in large-signal theory, we obtain different results.

4. Applications

Although the history of the four-wave mixing effect is not yet three years old, the tentative applications that have already been proposed are rich and varied. Here we will emphasize applications in the field of coherent optical adaptive technology only.

1. Coherent optical adaptive technology applications [23]

So-called coherent optical adaptive technology (COAT) consists of using a number of systems to adjust the wave-planes of transmitted beams of light to compensate the phase distortion caused in optical channels (both atmospheric and optical chaining). The most hopeful methods of these applications are stimulated Brillouin back-scattering and degenerate four-wave mixing.

To correct the wave-plane of an excited wave that has passed through the atmosphere, we may select the method shown in Fig. 4. When an uncorrected optical pulse is projected onto a target, it is reflected back diffusely by

the target. This back-pulse then passes through a distorting medium and reaches the receiver as a wave-plane with aberrations. By using a nonlinear phase conjugate device to generate the phase conjugate of this wave-plane having aberrations, after coherent amplification and raising to the required power level, this phase conjugate pulse may be propagated through the atmosphere once again, and its phase coherence will be restored, thus focusing the entire beam. The return pulse from a distant target is very weak. The significance of this is that particularly high gain systems are required to overcome the loss. Several years ago, laser fusion systems were developing high gain techniques to handle 1.06 microns and 10.6 microns. Now they can achieve gain of approximately 60 decibels.

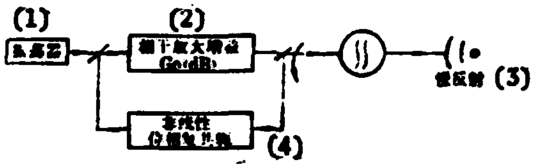

Fig. 4. Using nonlinear phase conjugates to correct atmospheric distortion.

Key: (1) Oscillator; (2) Coherent amplification gain; (3) Diffuse reflection; (4) Nonlinear phase conjugate.

The system shown in Fig. 5 may be selected to correct the wave-plane distortion in a laser amplifier chain. The pulse emitted from the oscillator passes through a power amplifier chain and is propagated in the direction of the target. The diffuse reflected beam from the target passes through the amplifier chain and is distorted. The beam with distorted wave-plane passes through small-signal amplification and generates a conjugate reflected beam in the nonlinear phase conjugate device. This reflected beam is propagated in the same direction as the incident beam and the aberrations are compensated. The first pulse projected towards the target is called the illumination pulse (in this case the high-gain amplifier system is not functioning, using only the laser pulse of the oscillator), and the diffuse pulse reflected back is the corrected pulse. So long as there is no clear change in the medium forming the optical path during the time that the corrected pulse is being reflected back (between 10^{-3} and 10^{-6} seconds approximately), this compensation will be

complete. In principle we must ensure that the conditions of the amplifier gain and the activation of the medium do not change during the round-trip time of the corrected pulse. If required, this method may be used to generate a periodic pulse chain and each preceding corrected pulse may serve as the subsequent probe pulse.

In addition, intracavity degenerate four-wave mixing techniques may be used to enhance wave-planes propagated by a laser [16]. Yariv et al. [24] have used the four-wave mixing method to compensate color scattering in fiber optic transmission.

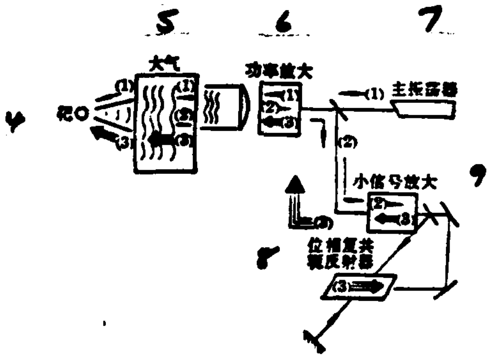

Fig. 5. Basic geometry for using nonlinear phase conjugate waves to correct atmospheric and laser induced distortion.

Key: (1) Illuminator pulse; (2) Scattered return pulse; (3) Corrected pulse; (4) Target; (5) Atmosphere; (6) Power amplification; (7) Primary resonator; (8) Small-signal amplification; (9) Phase conjugate reflecting device.

2. Other applications

1. Ultra-high-speed optical gating

Because three of the four waves in the above-mentioned four-wave mixing process are incident waves, any one of these three waves may be blocked and the retroflected wave will fade. There is a relationship between the response time and the relaxation time of the nonlinear medium (in the case of an absorber, this is the life of the excited state and in the case of a transparent medium,

this is the time taken by the induced polarization to assume a direction). In the case of a transparent medium and a number of large-molecular absorbers, this response time is very short. For this reason, this technology may be used to develop ultra-high-speed optical gating. Bloom et al. [25] have discussed this technology.

2. Two-photon spectroscopy

In four-wave mixing, when a nondepleted pump beam is propagated in the opposite direction, the geometry uses the method of Doppler-free broadening from two-photon spectroscopy. In the case of one-photon, the transparent medium absorbs one photon from each beam and is excited to the two-photon absorbing highly excited state. When fluorescent quantum efficiency is low, and the nonlinear polarization of the medium is $\chi^{(3)}$ (in conventional two-photon fluorescent spectroscopy, the level of fluorescence and $\chi^{(3)}$ are proportional, and the nonlinear reflectivity of degenerate four-wave mixing and $|\chi^{(3)}|^2$ are proportional) using the degenerate four-wave mixing method to research Doppler-free broadening of two-photon spectroscopy is very effective [26]. We have observed two-photon resonance-enhanced degenerate four-wave mixing [27]. Using an Nd^{3+}: YAG tuned Q 1.06 micron laser and a 5 x 10^{-4} gram molecule density medium such as a ruby light 6G alcohol solution, with a length of 5 millimeters and a pump intensity of 71 millijoules, the nonlinear reflectivity can reach 14%. This technology provides yet another path for the development of highly excited states [28].

3. Measuring impurity migration

Hamilton et al. [29] used degenerate four-wave mixing technology to measure the spatial migration rate of diluted impurities in condensed media. This is because incident light has a fixed polarizability. The direction of polarization of the backward reflected wave is in the opposite direction to that of the incident object wave. If turning of the plane of polarization should occur, there will be a relationship between the turn angle and the migration speed. Thus if this turn angle can be measured, the migration speed may be conveniently obtained.

4. Ultra-narrow-band filters

In the case of resonant absorbers, particularly atomic gas media which have very narrow absorption lines, in degenerate four-wave mixing, the resonance gain effect is very sensitive to wave-length change. Hence if we are using a narrow spectrum resonant absorber, and if the incident object wave has a fixed bandwidth, only that radiation falling within the atomic absorption bandwidth will exhibit clear resonance gain. For this reason, even if the incident object wave has a broad spectral distribution, the backward reflected wave will have only the narrow spectrum of the atomic absorption. D. M. Pepper and W. L. Abrams [30], and J. Nilsen and A. Yariv [31] analyzed applications of this near-degenerate four-wave mixing effect in narrow band filters. This type of filter has a large field of view and may serve as a gain filter. In addition the conjugate characteristics of the output field may be used to increase the signal-to-noise ratio. The maximum bandwidth of this type of filter is that of the excited laser itself.

5. Measuring the third-order polarization index of a medium

There is a relationship between the third-order polarization index of a medium and many nonlinear optical effects such as stimulated Raman scattering, two-photon absorption, coherent anti-Stokes' scattering, third-harmonic tuned waves, and four-wave mixing. Thus the precise measurement of the third-order polarization index $\chi^{(3)}$ is very important, and yet, although all kinds of methods have already been proposed to measure this [32], the results produced by the different methods differ greatly, and the accuracy of measurement generally is not high. Since we know that in degenerate four-wave mixing, the nonlinear reflectivity and $|\chi^{(3)}|^2$ are proportional, we may establish the third-order polarization index of the medium by measuring the nonlinear reflectivity. We have used this method to measure the third-order polarization index of many transparent liquid and glass media [33]. By using this method, we can, in principle, obtain higher accuracies.

6. Other applications

In degenerate four-wave mixing, A_1 is the nondepleted reference wave, A_4 is the object wave, and A_2 is the reproduction wave. The nonlinear medium must act on A_1 and A_4 simultaneously before there can be a nonlinear coupling

effect. Clearly if the delay times of A_1 and A_4 are changed, and these two pulses overlap the nonlinear medium at different moments, the output intensity of the backward wave will be consequently changed. We may therefore compute the ultra-short incident pulse width by measuring the change in the backward wave intensity. This is another autocorrelation technique, and although it is comparable to frequency-doubling methods normally adopted, it can provide higher efficiencies (a medium with a sufficiently high third-order nonlinear polarization index must be selected together with appropriate geometry).

If the medium is an absorber, and if the delay time of A_2 is changed, we may measure the high-excitation-state life-time of the resonant absorber. This technique is particularly suitable for macromolecular research into very short lifetime excited states.

In addition, if the frequencies of all four waves in degenerate four-wave mixing are equal, in practice we may remove the degenerate component. If we let $\omega_1 = \omega_4 = \omega$, then $\omega_3 = \omega_1 + \omega_2 - \omega_4 = \omega_2$. This demonstrates that we may use ω_2 to reproduce information recorded by ω_1. From the standpoint of the set-up angle of real-time holography, this is very well understood. Moreover, the phase conjugate characteristic enables this method to yield reproduced images of high resolution. Clearly we may use this technique to achieve nonlinear frequency change and infrared image conversion [34].

If we let $\omega_1 - \omega_4 = \omega_s$, in which ω_s is the normal resonant frequency of the medium and $\omega_2 = \omega_1$, then, in this case, $\omega_3 = \omega_1 + \omega_s$ and the backward reflected wave will correspond to the anti-Stokes' frequency. This non-degenerate four-wave mixing technique is very similar to coherent anti-Stokes' scattering. However using this technique utilizes the pump beam more efficiently and can isolate an interference signal better.

H. Hsu proposed the use of nonlinear reflecting mirrors in the collecting of solar energy, to control the precise position of energy collectors on the ground. This system may also be used in the precision tracking of flying targets [35].

There are two characteristics of phase conjugate mirrors (PCM): the first is that they can supply the phase conjugate reflected beam of an incident

beam, and the second is that the reflected beam is the backward beam of the incident beam. PCMs may serve as one of the reflecting mirrors in a laser oscillator. Because an oscillator incorporating this type of mirror has particular superiority and stability [36], a laser propagated in a cavity will interact with the stable activation area of a laser medium and will influence the automatic compensation of phase distortion in the medium. We may thus hope to achieve high brilliance laser output in high energy pump states.

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